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EFFECT OF OSCILLATING TABS ON A JET-IN-CROSS-FLOW

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Abstract

A novel technique for active control of a jet-in-cross-flow is explored in this study. Two triangular tabs are placed at the 90° and 270° edges of the jet orifice, relative to the direction of the cross-flow. A slight asymmetry in the placement of the two tabs is reversed periodically. This causes a profound oscillation of the flow field that persists as far downstream as the measurements were permitted by the facility (100 orifice diameters). Parametric dependence of the unsteadiness and its impact on the flowfield has been investigated preliminarily. It is found that the effect becomes increasingly pronounced with increasing value of the momentum flux ratio (J). However, there is little or no effect at low values of J in the range, $J < 15$. The effective frequencies of oscillation are low—more than an order of magnitude lower than that found with oscillatory blowing technique in previous studies. The flow mechanism apparently involves a direct perturbation of the counter-rotating stream-wise vortex pair of the flow.

1. Introduction

The configuration of a jet-in-cross-flow occurs in numerous technological applications. One of its usages has been in flow control. Past research focused on its application, for example, for separation control in inlets and ducts, over blades and wings, for thrust vectoring with nozzle flows as well as for enhanced mixing in combustors.

The majority of the research involved steady or continuous jets discharged into the cross-flow. Of late, there is a growing interest in 'active control' by imparting an unsteady component to the jet issued

into the cross-flow. One earlier work¹ observed a remarkable organization of the 'wake vortices' when a perturbation was imposed on the jet. Several recent studies²⁻⁵ addressed the flowfields of pulsed jets in a cross-flow. The pulsed jet penetrated more and mixed better with the cross-flow compared to an 'equivalent' continuous jet. Earlier, it was demonstrated that oscillatory blowing rather than steady blowing was more effective in boundary layer separation control over airfoils.⁶ There have been CFD investigations for the effect of pulsed injection on nozzle flows,⁷ as well as modeling efforts for effect of pulsed blowing for separation control over various lifting surfaces.⁸

The effect of periodic perturbation on an isolated jet in cross-flow is investigated in the present experiment. While in all the cited studies a perturbation was imposed in the flow-rate of the jet, a method of mechanical perturbation is pursued in this investigation. The premise and the potential advantage of the method are elaborated next.

In an earlier investigation⁹ vortex generators (tabs) were tried with the aim of increasing mixing and penetration of a jet-in-cross-flow. It was thought that if a tab were placed on the downstream edge of the jet orifice, at 180° relative to the direction of the cross flow, there would be an increased penetration. For then the vortex pair generated by the tab would be of the same sign as the counter-rotating vortex pair (CVP, sometimes also referred to as the 'bound vortex pair'.) An augmented CVP was expected to cause an increased penetration. However, after several trials it became apparent that the flow was 'stubborn' and the potential for increased penetration was not promising. The underlying mechanism for this lack of effect has been addressed in the cited reference.

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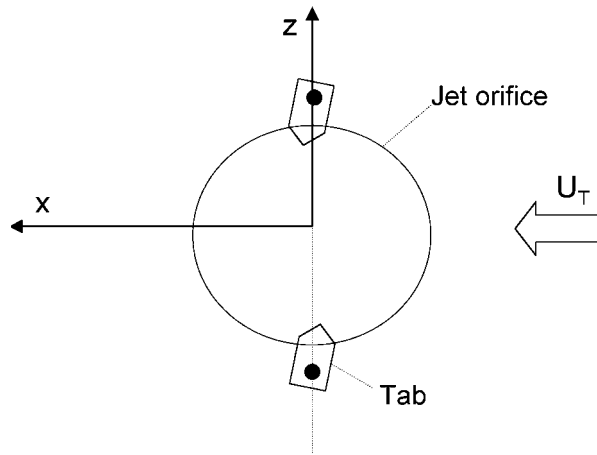


Fig. 1 Schematic of jet orifice and tab configuration. Two tabs are in the extreme counter-clockwise (CCW) position.

During those deliberations,⁹ certain tab configurations produced effects that were also of interest, e.g., a decreased penetration of the jet that could be useful in film-cooling application.¹⁰ Another specific effect, noted in Ref. 9, forms the basis of the present investigation. Cursory surveys (unpublished) indicated that a slight asymmetry in the placement of two tabs, as shown in Fig. 1, would upset the CVP. One component of the pair became stronger causing high speed flow to spill towards it. When the asymmetry in the tab placement was reversed the opposite vortex would become stronger spilling the jet the other way.

Thus, it was thought that a periodic oscillation of the two tabs between the 'clockwise' (CW) and 'counter-clockwise' (CCW) asymmetric configurations (Fig. 1) would result in a side-to-side unsteady motion of the jet that might invigorate mixing. It was apparent that the principle of flow perturbation would be different from that of pulsed blowing. With pulsed blowing, the direct effect was to modulate the azimuthal vorticity of the jet shear layer. With the tab oscillation, it seemed that the effect would be a direct modulation of the CVP. The CVP being a dominant feature of the flow persisting far from the orifice, the tab oscillation was expected to influence a large extent of the flow-field. The aim of the present investigation was to explore this effect, its parametric dependence, and impact on the flowfield.

2. Experimental facility

The experiments were conducted in an open circuit low-speed wind tunnel with 30 x 20 inch test section. The jet was discharged from a $\frac{3}{4}$ inch diameter (D) orifice on the floor of the tunnel. The orifice was located on a round disk made of clear plastic and flush mounted with the test section floor. The disc also housed the tab oscillation mechanism. A picture of the assembly mounted on the tunnel floor is shown in Fig. 2(a). Fig. 2(b) shows the mechanism with the cover plate taken off.

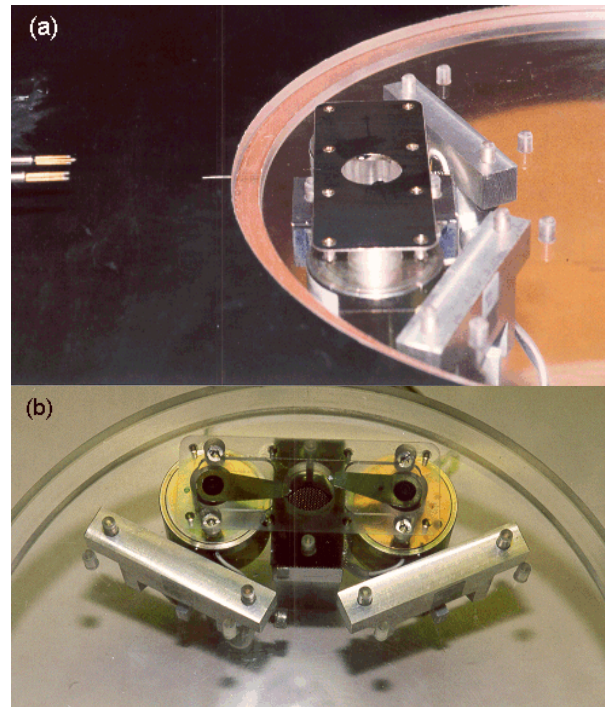


FIG. 2 Picture of experimental set-up. (a) Assembled apparatus installed on wind tunnel floor. On the left are two X-wire probes for flow-field survey. (b) Tab oscillation mechanism.

There are two 'relays' mounted underneath the round disc that are capable of imparting angular displacement to the two tabs. When the relays are turned off the tabs are located in the CCW position as shown in Fig. 1. When the relays are turned on the two tabs are displaced in angle to produce a reverse CW configuration. The limits of the angular displacement could be adjusted with set-screws in the mechanism. For most of the data, the amplitude was set such that the tip of a tab moved by about $\pm 0.05D$ from its mean position. Square-waves of opposite polarity from a function

generator activated the relays. The relays allowed oscillation frequencies up to 80 Hz.

Each tab had a base width of $0.25D$. The total area blockage due to the two tabs was about 4% of the orifice area. The jet flow was provided through a 4.5 inch long pipe section having a flow-conditioning screen located 1 inch upstream of the exit. The other end of the pipe was connected to compressed air supply through a flexible hose. This simple arrangement had to be chosen, instead of a plenum with better flow conditioning, because of space constraints due to the proximity of the relays. With the tunnel flow turned off and without the tabs, cursory surveys indicated that the flow was uniform at the jet exit. An orifice meter fitted to the supply line was used to monitor the mass flow rate that determined the average jet velocity (U). The area blockage was taken into account in calculation of U_j for the tab cases.

Hot-wire measurements were performed with two adjacent X-probes. One was placed in the ' u - v ', and the other in the ' u - w ', orientation. The probes were spaced 1.1 cm apart in the span and were traversed so that they sampled at the same points in space, but at different times. The v and w data were corrected for the error introduced by U -gradients and finite separation of the sensors in each X-array according to standard procedures. Further description of the experimental procedure can be found in earlier publications.¹¹ Phase-averaged measurements with the two X-wires were carried out using the signal activating the tabs as reference. In addition, the raw signal of a single element of the u - w probe (the one nearest to the floor) was analyzed by a spectrum analyzer (Nicolet 660B) for tracking phase and relative amplitude of the fundamental.

The co-ordinate system is shown in Fig. 1. The direction of the tunnel flow, x , will be called 'streamwise' direction. The direction in z would be referred to as 'spanwise'. That in the third direction (y) would be referred to as 'transverse'. In the following, distances are nondimensionalized by the jet diameter, D , and the velocities by the tunnel speed, U_T .

3. Results

Streamwise velocity distributions on the cross-sectional (y, z) plane, at $x/D = 8$, are shown in Fig. 3. Figure 3(a) shows the distribution for the no-tab case. The expected 'kidney shaped' distribution can be observed. Figures 3(b) and (c) are for *stationary* tabs located in the CW and CCW configurations, respectively. The flow-rate for the jet was held constant for these data. The flow blockage due to the tabs accounts for the difference in the value of J for the no-tab and tab cases. (Data for symmetrically placed tabs will be compared with the oscillating case at the end.) The characteristic tilt of the high-speed fluid to the left for the CW case is clearly seen in Fig. 3(b). With the CCW configuration, in Fig. 3(c), there is a tilt in the reverse direction. However, the effect in the CCW configuration is less pronounced. This is further addressed shortly.

Streamwise vorticity distributions corresponding to the configurations of Figs. 3(a)-(c) are shown in Figs. 4(a)-(c). For the no-tab case, the counter-rotating vortex pair (CVP) is observed clearly. For the CW case (Fig. 4b), peak vorticity in the positive element of the CVP has increased from 0.65 to 0.76 but the location of the core has remained approximately the same. The negative element of the CVP, on the other hand, has been altered drastically. It has diffused with the minimum changing from -0.64 to -0.41 . It has wrapped over the positive element and in the process a region of concentrated negative vorticity emerged near the tunnel floor. A reverse, albeit less pronounced, effect has taken place with the CCW configuration in Fig. 4(c).

At first the less pronounced effect with the CCW configuration was thought to be due to small differences in the two tabs. Perhaps, with the CCW configuration there was actually a 'bias' towards the CW direction due to placement or imperfections in the tabs. In order to verify this, z -profiles of U were measured at a fixed height (y) while varying the angular displacement of each tab. After several trials it became apparent that only a slight displacement in the CW direction would tilt the high velocity core to the left as in Fig 3(b). However, a deliberately large displacement in the CCW direction was needed to tilt the core to the right. This ruled out imperfections in the tab geometry or their placement as being responsible for the discrepancy.

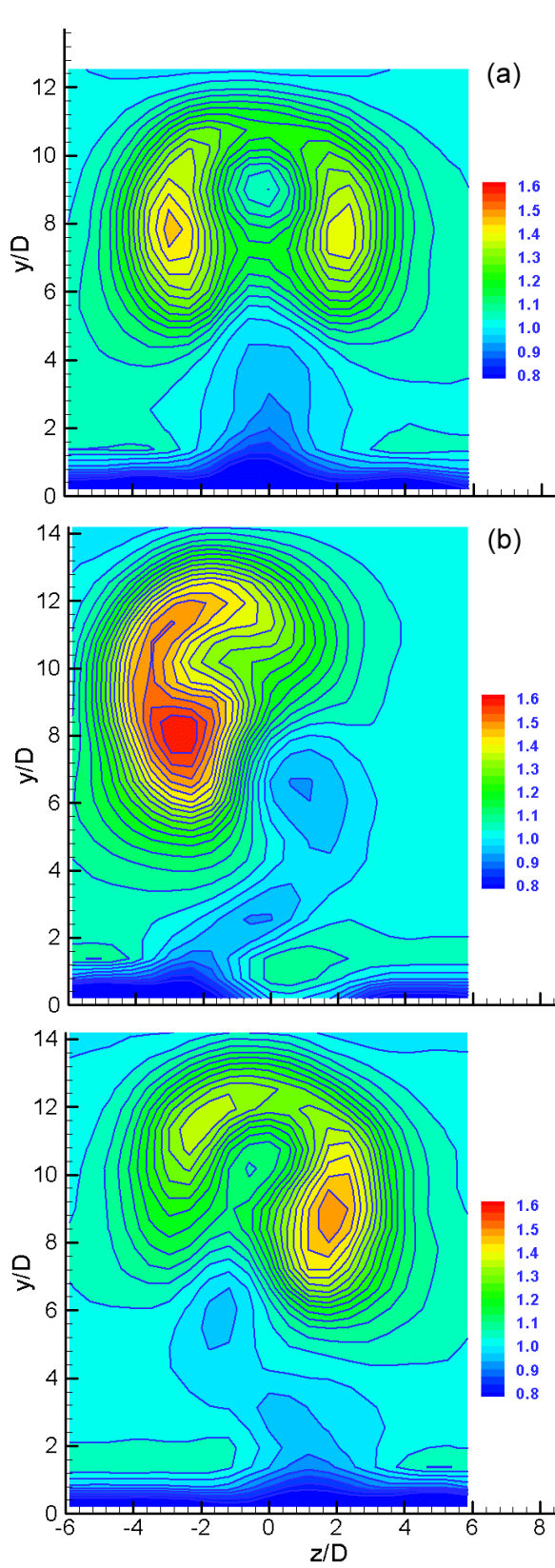


Fig. 3 Streamwise velocity (U/U_T) distribution on cross-sectional plane at $x/D = 8$, $U_T = 21$ fps. (a) No-tab, (b) 2 stationary tabs CW, (c) 2 stationary tabs CCW. $J = 44$ for no-tab case and $J \approx 48$ for tab cases.

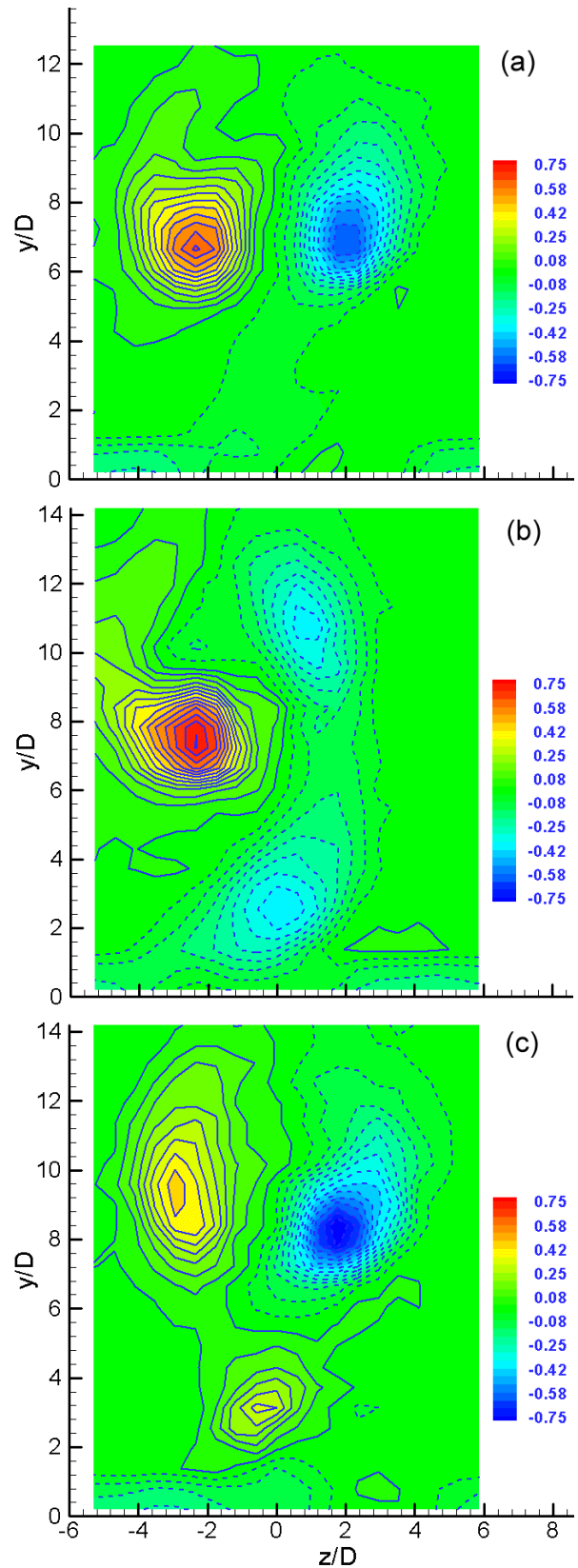


Fig. 4 Streamwise vorticity ($\omega_x D/U_T$) distribution corresponding to the cases of Fig. 3. (a) No-tab, (b) 2 stationary tabs CW, (c) 2 stationary tabs CCW.

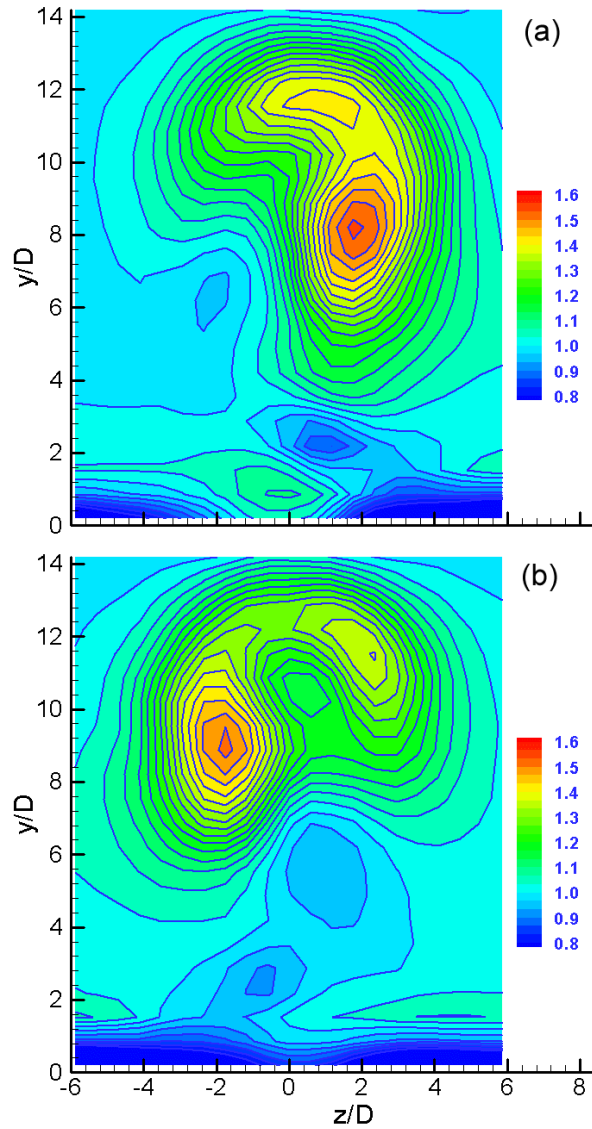


Fig. 5 Streamwise velocity (U/U_T) distribution at $x/D = 8$ for $U_T = 21$ fps and $J \approx 48$. Orifice plate rotated by 180° . (a) 2 stationary tabs CCW, (b) 2 stationary tabs CW.

Attention then fell on the possibility of a residual swirl in the tunnel flow. As a diagnosis, the disc with the orifice (Fig. 2) was turned 180° and the field measurements repeated. With the disc turned, the CCW configuration remained CCW but the left and the right tabs were interchanged. The observed bias should not have changed had it been due to a peculiarity in the tunnel flow. However, with the new CCW configuration, as shown in Fig. 5, the tilt to the right was more pronounced while tilt to the left with the CW configuration was not easily achieved. This ruled out any peculiarity of the tunnel flow as being the source of the discrepancy.

Finally, a connection could be established to a curvature in the supply hose. When the supply hose was straightened the discrepancy alleviated. The issue was pursued at length, and described here, as it could have impacted the oscillatory flow under study. It also underscores the sensitivity of the flow that should be noted in related experiments or applications in the future. The rest of the data in this paper are for the original configuration of the disc with a straightened supply hose.

With the tabs oscillated at a fixed frequency and amplitude, the effect of various flow parameters was first explored by simply inspecting the hot-wire signal. It soon became clear that the effect was noticeable only when the jet-to-freestream momentum ratio ($J = (U_j/U_T)^2$) was high. In fact, the surveys were started at $J = 16$ and the impact on the flow field appeared disappointing. The effect became clearer at higher J as demonstrated in Fig. 6. With the given position of the hot-wire probe, the flow periodicity can be seen to become increasingly pronounced with increasing value of J .

In order to ensure an unambiguous effect on the flow-field, $J = 48$ was chosen for further exploration. Figure 7 shows that the periodicity in the flow, although becoming weaker and more random with increasing distance, persisted to the farthest downstream location in the test section ($100D$). The periodicity was further confirmed by spectrum of the hot-wire signal (not shown) that exhibited an unambiguous spike at the oscillation frequency. This result corroborated the expectation (§1) that the effect must be persistent because the technique modulates the CVP.

The amplitude and phase of the fundamental (at the oscillation frequency, f_p) were measured via spectral analysis of the hot-wire signal (§2). Typical phase profiles in y are shown in Fig. 8. At each x -station there is a phase jump very near the floor that could not be resolved conclusively because the probe arrangement did not permit measurement all the way to the floor. Farther away, near the edge of the boundary layer, there is a phase jump by approximately 180° . This indicates that the unsteady velocity within the boundary layer, at a given instant, is opposite to that within the freestream directly above. In the freestream, a systematic phase variation with x can be observed. This variation is shown in Fig. 9. From the slope of the curve in the x/D range of 10-20, the phase velocity (U_c) is calculated to be about $0.9U_T$. Phase measurements at two x -locations for several other

frequencies, from 2 to 40 Hz, yielded a value of U_∞/U_T in the range of 0.9 -1.0.

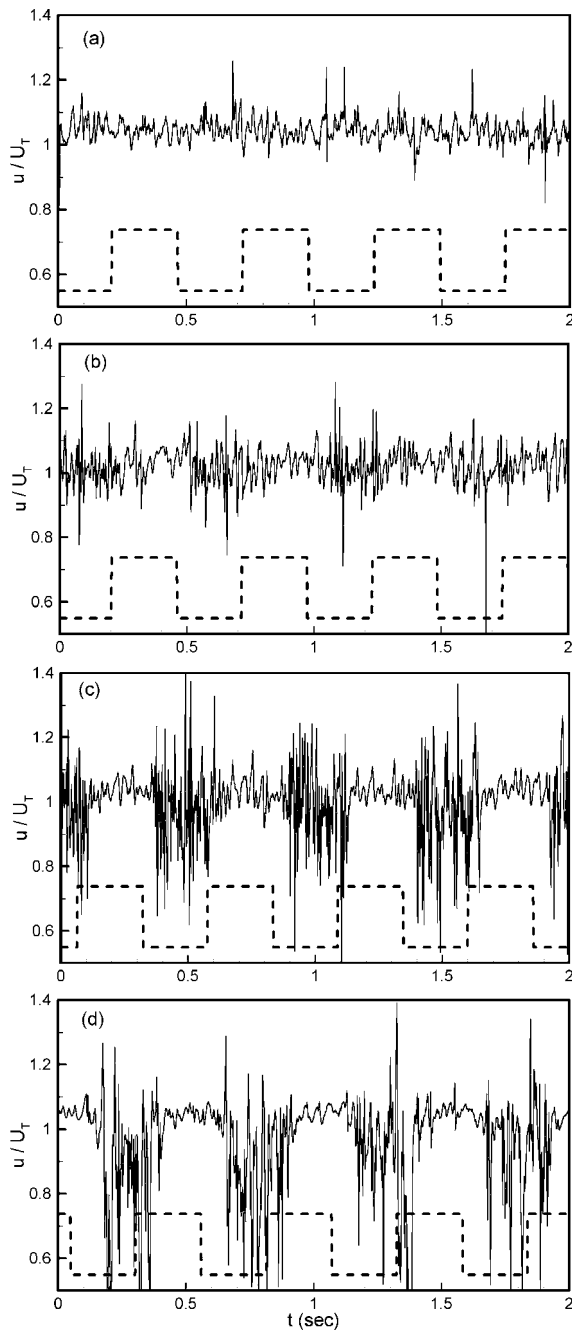


Fig. 6 Time trace of hot-wire signal at $x/D = 8$, $y/D = 0.8$, $z/D = 2.0$. Signal activating relays shown by dashed line, $f_p = 2$ Hz. (a) $U_T = 25.2$ fps, $J = 10.1$; (b) $U_T = 25.2$ fps, $J = 17.3$; (c) $U_T = 25.1$ fps, $J = 33.5$; (d) $U_T = 14.1$ fps, $J = 105$.

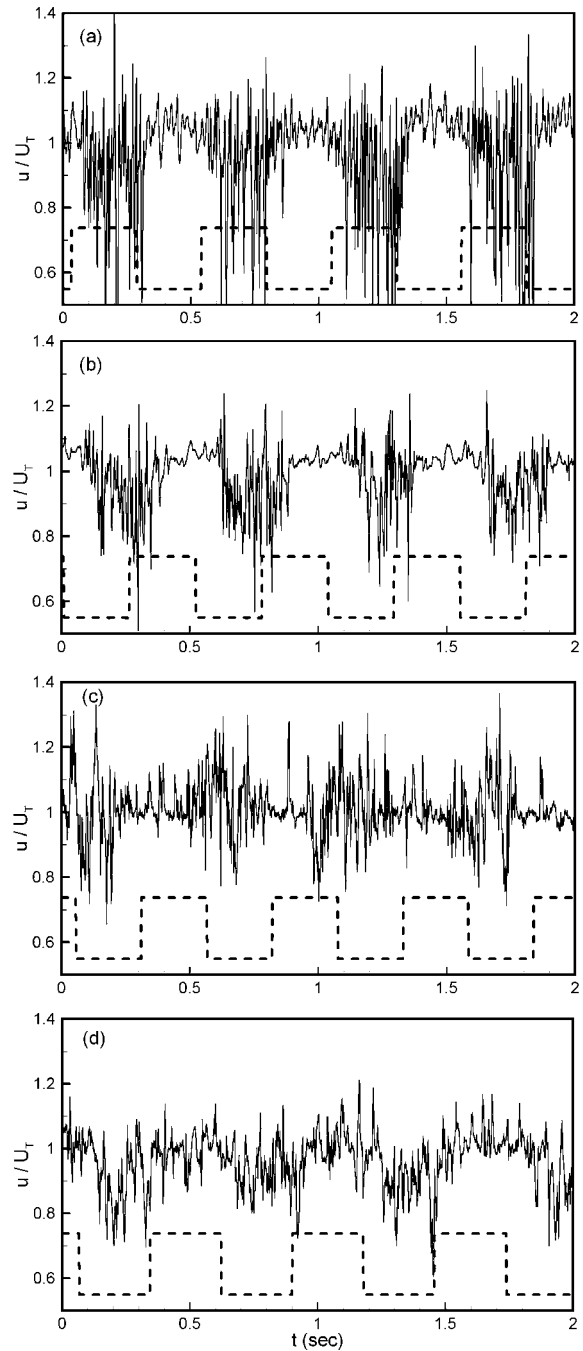


Fig. 7 Time trace of hot-wire signal for $U_T \approx 21$ fps and $J \approx 48$. Signal activating relays shown by dashed line, $f_p = 2$ Hz. (a) $x/D = 4.0$, $y/D = 1.0$, $z/D = -1.5$; (b) $x/D = 19.5$, $y/D = 1.2$, $z/D = -2.0$; (c) $x/D = 50.0$, $y/D = 12.0$, $z/D = -4.0$; (d) $x/D = 100.0$, $y/D = 12.0$, $z/D = -8.0$.

In Fig. 10, the amplitude of the fundamental, measured at a fixed location, is shown as a function of the oscillation frequency (f_p). As stated before, these data were obtained by analyzing the signal from one element of the X-wire without invoking the calibration. Thus, the amplitudes (r.m.s. mV) are in an arbitrary scale but should be

adequate to infer on the relative response of the flow-field. The data exhibit that the flow-field responds to the tab oscillation in a range of low frequencies. At higher frequencies the amplitude gradually drops off. It is not clear if any significance can be attached to the slight undulations in the low frequency end. The 'response' may be considered basically constant up to about 25 Hz. The amplitude then drops off with increasing frequency. For the given J and U_T , no flow oscillation is detected at the measurement location for $f_p > 55$ Hz. Limited measurements, at the same probe location for $J = 96$, also showed a similar trend in the response—flat up to about 20 Hz and disappearing at frequencies higher than about 60 Hz.

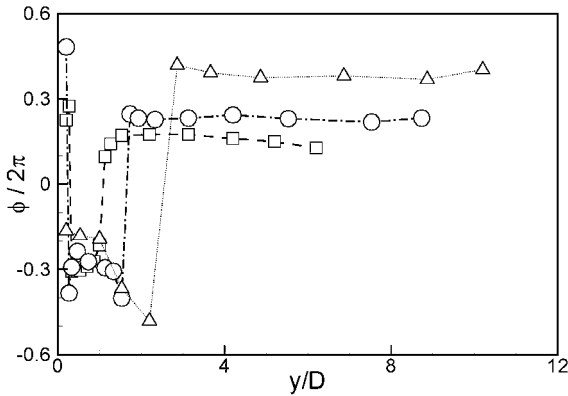


Fig. 8 Variation of phase in the transverse (y) direction at $z/D = -2$, $U_T \approx 21$ fps and $J \approx 48$, $f_p = 4$ Hz. \circ , $x/D = 4$; Δ , $x/D = 8$; \square , $x/D = 19.5$.

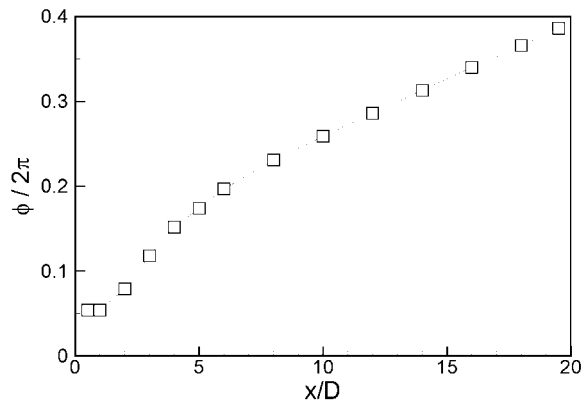


Fig. 9 Variation of phase in the streamwise direction; $y/D = 5$, $z/D = -2$, $U_T \approx 21$ fps and $J \approx 48$, $f_p = 4$ Hz.

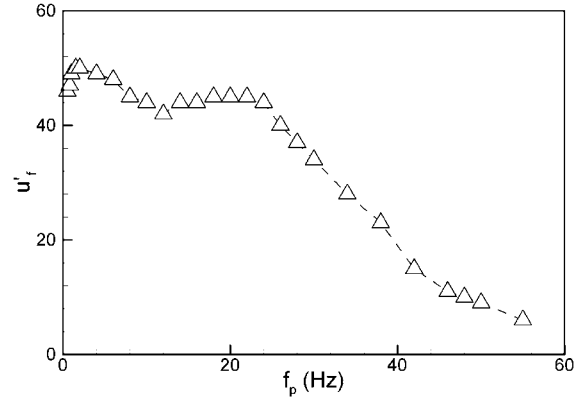


Fig. 10 Fundamental amplitude (arbitrary scale) versus f_p , measured at $x/D = 8$, $y/D = 5$, $z/D = -2$, $J \approx 48$.

The upper limit of the range of strong response in Fig. 10 ($f_p = 25$ Hz) corresponds to a Strouhal number ($f_p D/U_i$) of about 0.01. The fact that the effective f_p -range remains approximately the same at higher J implies that the effective Strouhal numbers are even smaller in the latter conditions. This contrasts effective Strouhal numbers in the range of 0.2- 0.4 observed with pulsatile blowing.^{2,3} As stated in the introduction, pulsatile blowing acts on the jet's azimuthal vorticity. In the present case, obviously, the CVP responds to perturbation only at very low Strouhal numbers.

Transverse profiles of streamwise mean velocity (U), r.m.s. turbulence (u') and r.m.s. fundamental amplitude (u'_1), measured at a fixed (x, z), are shown in Fig. 11 for four different values of J . (While u'_1 is in arbitrary scale, U and u' are correctly represented.) The peaks in the U -profiles in (a) can be seen to shift upwards with increasing J . This is consistent with the general behavior of a jet-in-cross-flow. At the highest J (=190), the peak is just outside the range of the traversing mechanism. The locations of U -maxima (y_{max}) may be compared with correlations for steady round jets in cross-flow, $y_{max}/D = (x/D)^{0.33} J^{0.43}$, (see, e.g., Ref. 12). The predictions for y_{max}/D for $J = 23, 48, 94$ and 190 are 7.7, 10.5, 14.1 and 19.1, respectively. There is reasonable agreement at lower J but at higher J the locations are underpredicted. Thus, at higher J , the tab oscillation may have caused a somewhat higher jet penetration. However, it will be shown in the following that the higher penetration is already produced by the stationary tabs and no further increase is caused by the oscillation.

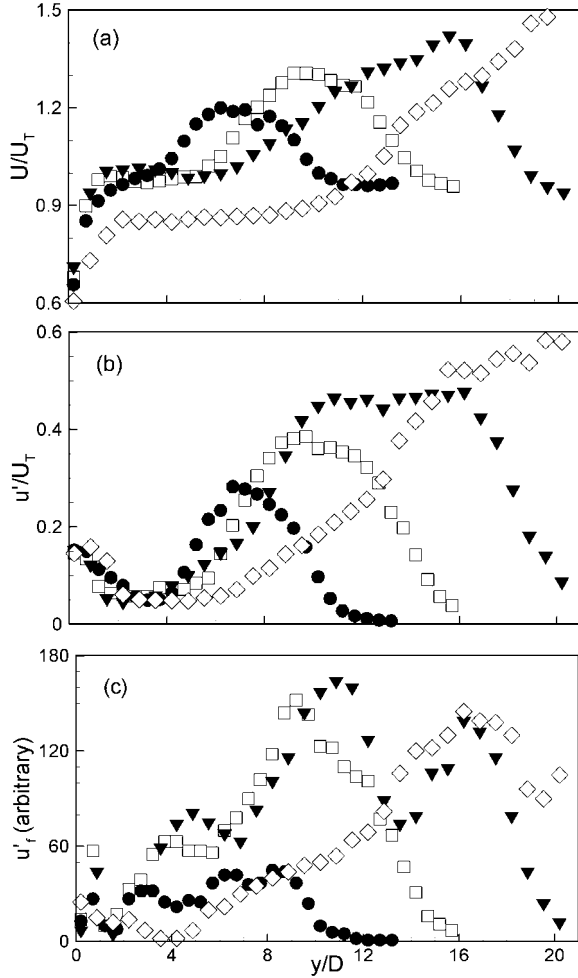


Fig. 11 Transverse profiles at $x/D = 8$, $z/D = -2$, $f_p = 4$ Hz. \bullet , $U_T = 21.6$ ft/s, $J = 23$; \circ , $U_T = 21.6$ ft/s, $J = 48$; \blacktriangledown , $U_T = 21.6$ ft/s, $J = 94$; \diamond , $U_T = 14.7$ ft/s, $J = 190$. (a) Mean velocity, (b) turbulence intensity, (c) fundamental amplitude.

The u' -profiles in Fig. 11(b) exhibit that peak turbulence intensity occurs approximately in the region of peak mean velocity. This is not unexpected because the turbulent activity is associated with the high momentum jet fluid. The fundamental amplitude profiles (Fig. 11c) show that the flow barely responds to the oscillation at the lowest J ($=23$). There is a strong response at $J = 48$ with the location of u'_r -peak approximately coinciding with that of u' -peak. At $J = 94$, apart from some undulations at lower y , the u'_r -profile has developed dual-peaks, one occurring at $y/D = 11$ and another at $y/D = 17$. The latter location coincides with the locations of u' - and U -peak. The $u'_r(y)$ data at the highest J ($=190$) also indicate the likely presence of dual-peaks – one at $y/D = 17$ and another just outside the measurement domain. Referring back to Figs. 3(b) and (c) it appears that

the peak at the lower y occurs due to the periodic formation of the high velocity core (see also phase-averaged data in the following). The peak at the higher y is apparently associated with the lateral motion of the region of high U . Note that in all cases, including the lowest J , there is a peak within the boundary layer. The flow oscillation in the free-stream is accompanied by a ‘sympathetic’ oscillation in the boundary layer. We have seen before that the direction of the unsteady motion in the boundary layer is approximately opposite to that in the free-stream.

Phase-averaged measurements were conducted using the signal activating the tabs as reference. Data were obtained for nineteen equally spaced phases within the oscillation cycle. Spanwise profiles of phase-averaged streamwise velocity are shown in Fig. 12. For clarity, data are shown for a limited number of phases.

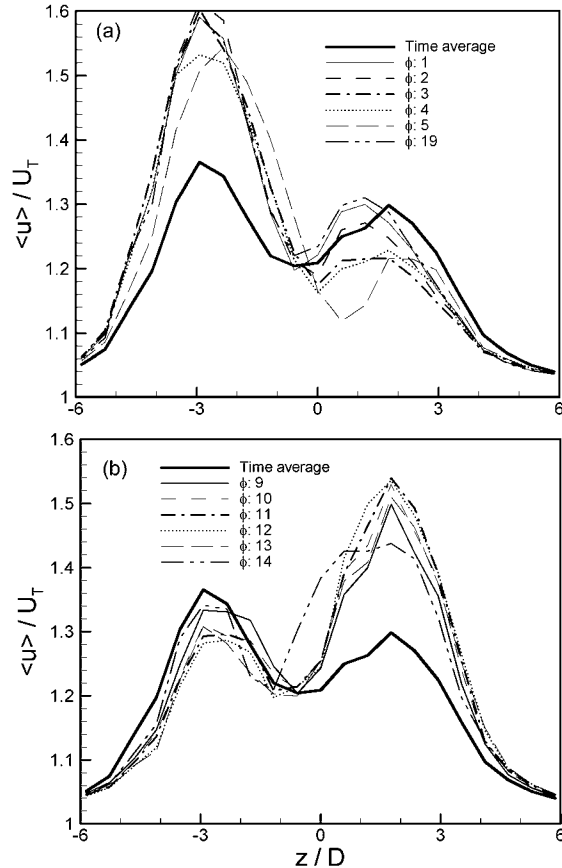


Fig. 12 Spanwise profiles of phase-averaged streamwise velocity for $f_p = 8$ Hz: $x/D = 8.0$, $y/D = 8.4$, $U_T \approx 21$ fps and $J \approx 48$. Data shown in (a) for 6 phases when the jet is on the left and in (b) for 6 phases when the jet is on the right.

The phases, chosen for Fig. 12(a), represent the condition when the high velocity core has spilled to the left. Those chosen for Fig. 12(b) are for the opposite part of the cycle. In each figure the time-averaged U -profile is also shown for comparison. It can be seen that for the majority of phases within the cycle, the high velocity core is either to the left or right. The flow transitions from one state to the other rapidly within two or three phase steps. Thus, for the chosen flow parameters with $f_p = 8$ Hz there is a ‘quasi-steady’ response of the flow-field. A square-wave oscillation produces a square-wave-like response.

Detailed phase-averaged velocity distributions are shown in Fig. 13 for indicated phases relative to the first frame (successive phases are 20° apart within the cycle). The side-to-side oscillatory motion of the flow-field with varying phase is clearly captured. The corresponding phase-averaged streamwise vorticity (not shown) exhibit a periodic switching approximately between the two states seen in Figs. 4(b) and (c).

In order to assess the overall impact on the flow-field, time-averaged surveys were conducted at $x/D = 8$. First, data were acquired with two stationary tabs placed symmetrically. Then, the measurements were repeated with the tabs oscillated at 8 Hz. Comparison with the stationary tab case, rather than with the no-tab case (Fig. 3a), was more appropriate to isolate the effect of the oscillation. Distributions of different flow properties are compared in Fig. 14. At the top is comparison of U -distributions. Recall from the discussion of Fig. 11 that the jet penetration was somewhat higher compared to the prediction for a round jet (without tabs) having equal exit area. The U -data in Fig. 14 reveal that the jet penetration is already high with the two stationary tabs ($y_{max}/D > 12$ as compared to a prediction of 10.5). With the oscillation, in fact, a slight decrease in the penetration has taken place together with a diffusion of the jet and spreading over a larger area. An increased spreading on a time-averaged basis is expected not only because of the quasi-steady motion but also due to increase in mixing associated with the unsteadiness. A similar comment can be made from the comparison of u' -distributions shown in the second row of Fig. 14. The turbulent stresses, w' and uw , shown in the lower two rows, more clearly exhibit the increased spreading. A similar inference is also made with and without tab oscillation at a higher J

of 96. This is shown by comparisons of U and w' only, for brevity, in Fig. 15.

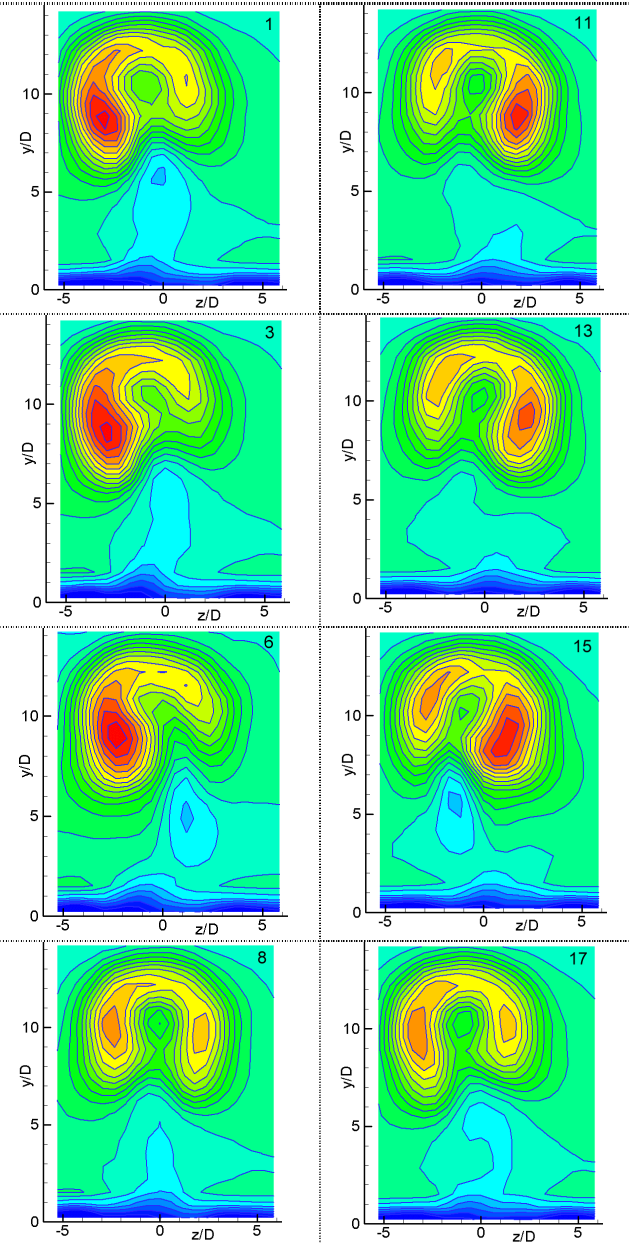


Fig. 13 Cross-sectional distributions of phase-averaged streamwise velocity, for indicated phase steps within the oscillation cycle, at $x/D = 8$; $U_T \approx 21$ fps and $J \approx 48$, $f_p = 8$ Hz.

The comparisons in Figs. 14 and 15 reveal that the tab oscillation has caused an increased spreading of the jet. However, the quasi-steady oscillation itself is expected to show up as ‘spreading’ on a time-averaged basis. How much of the observed spreading is due to actual turbulent mixing at smaller scales remains unclear at this time. It is possible that the spreading and

diffusion would be more pronounced farther downstream. This also remains unexplored at the present time due to facility constraints.

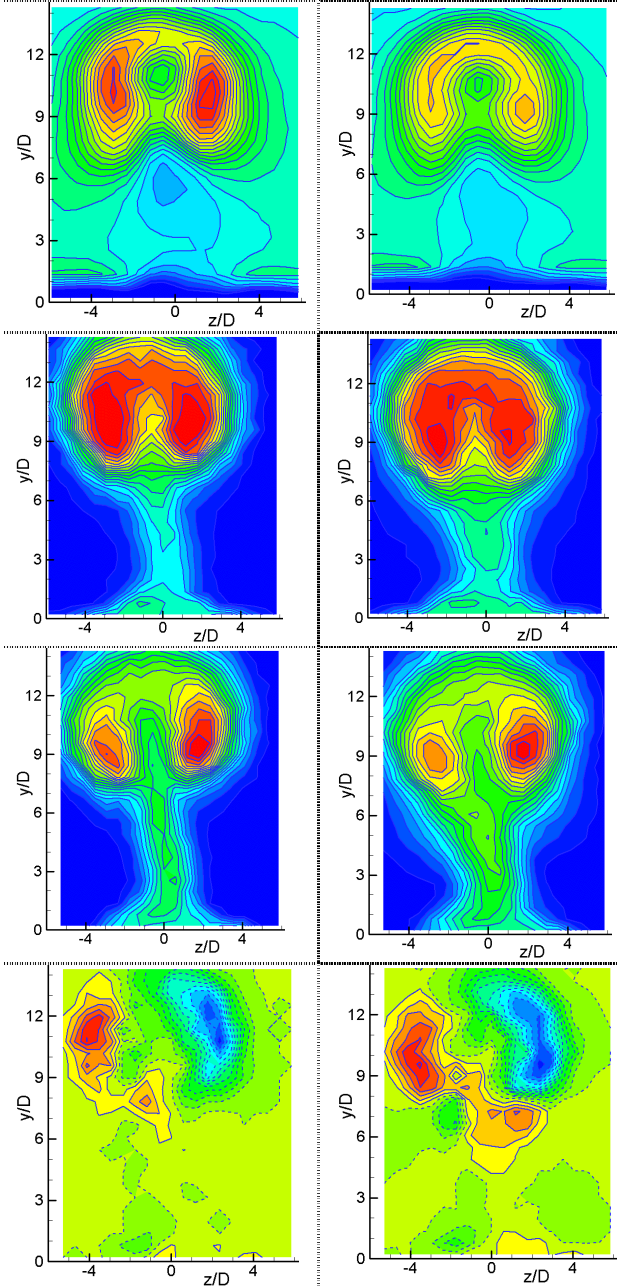


Fig. 14 Cross-sectional distributions of time-averaged properties at $x/D = 8$. Left column: for two stationary tabs (placed symmetrically); right column: for tabs oscillating at 8 Hz. $U_T \approx 21$ fps, $J \approx 48$. From top: row 1, U/U_T ; row 2, u'/U_T ; row 3, w'/U_T ; row 4, uw/U_T^2

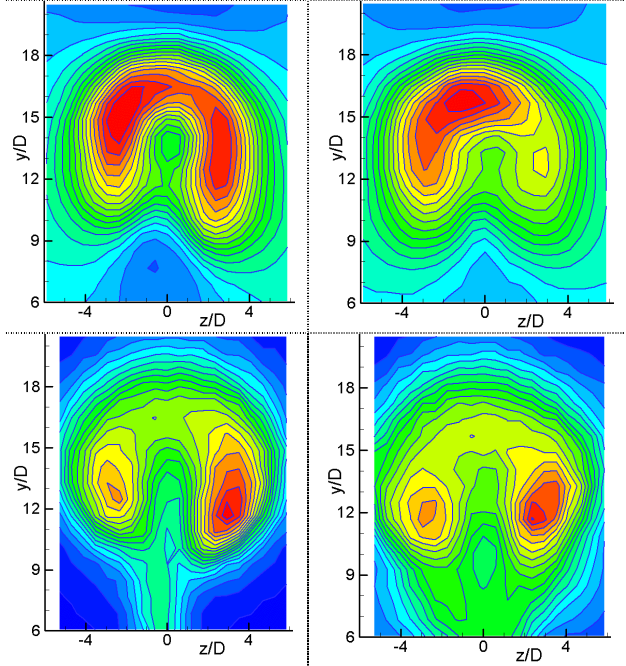


Fig. 15 Cross-sectional distributions of time-averaged properties at $x/D = 8$. Left column: for two stationary tabs (placed symmetrically); right column: for tabs oscillating at 4 Hz. $U_T \approx 21$ fps, $J \approx 96$. Top row, U/U_T ; bottom row, w'/U_T .

4. Concluding Remarks

A new technique for active control of a jet-in-cross-flow is explored in this study. Periodic oscillation of two tabs, placed at the 90° and 270° positions of the orifice, relative to the cross-flow, causes an oscillation of the entire flow field. The effect takes place via a perturbation at the 'anchor locations' of the counter-rotating streamwise vortex pair. Each element of the CVP goes through a periodic swaying motion. This is accompanied by a periodic side-to-side motion of the jet fluid.

The effect is found to be more pronounced at higher values of J . The flow does not appear to respond to the tab oscillation when J is less than approximately 15. For J higher than about 30 the effect is profound. It is detected as far downstream from the jet orifice as permitted by the facility (100 diameters).

At $J = 48$, detailed surveys were conducted. The flow responds in a low frequency range. The response, in terms of the fundamental amplitude measured at a fixed location, is approximately constant up to about 25 Hz. At higher frequencies

the response drops off and no oscillation is detected above 55 Hz. The effective frequencies of oscillation are low—more than an order of magnitude lower than that found with oscillatory blowing technique in previous studies.

It is found that the unsteady motion in the free-stream is accompanied by a 'sympathetic' response within the boundary layer. The phase of the motion in the boundary layer is opposite to that of the unsteady motion in the free-stream directly above. The unsteady disturbance is found to propagate downstream approximately at the speed of the cross-flow.

The flow oscillation causes an overall increase in the spreading of the jet. However, for the parametric range covered and at the measurement location ($x = 8D$) the increase is not dramatic. Also, a part of the observed spreading is simply due to averaging of the unsteady flow. It is possible that the 'cumulative' effect on spreading and diffusion would be much more at farther downstream locations. The results also lead to the notion that a potential exists for significant mixing enhancement by applying this technique to an array of jets-in-cross-flow. By appropriate phasing of the unsteady motion of the streamwise vortices a 'beneficial' interaction may be possible. These and other details will be explored in the future.

References

1. J.M. Wu, A.D. Vakili and F.M. Yu, "Investigation of the interacting flow of nonsymmetric jets in crossflow", *AIAA J.* 26 (8), pp. 940–947, 1988.
2. A. Eroglu and R.E. Breidenthal, "Structure, penetration, and mixing of pulsed jets in crossflow", *AIAA J.* 39 (3), pp. 417–423, 2001.
3. R.T. M'Closkey, J.M. King, L. Cortelezzi and A.R. Karagozian, "The actively controlled jet in crossflow", *J. Fluid Mech.*, 452, pp. 325–335, 2002.
4. H. Johari and G.S. Rixon, "Evolution of a pulsed vortex generator jet in a turbulent boundary layer", *AIAA Paper* 02–2834, 1st Flow Control Conference, St. Louis, MO, 24–26 June, 2002.
5. S. Naraynan, P. Barooah and J.M. Cohen, "Experimental study of the coherent structure dynamics & control of an isolated jet in cross flow", *AIAA Paper* 02–0272, 40th Aerospace Sciences Meeting, Reno, NV, Jan 14–17, 2002.
6. A. Seifert and L.G. Pack, "Active control of separated flow on a wall-mounted "hump" at high Reynolds numbers", *AIAA J.*, V. 40, No. 7, pp. 1363–1372 July, 2002.
7. D.N. Miller, P.J. Yagle, E.E. Bender, B.R. Smith and P.J. Vermuelen, "A computational investigation of pulsed injection into a confined, expanding crossflow", *AIAA Paper* 01–3026, 31st Fluid Dynamics Conference, Anaheim, CA, June, 2001.
8. B.H. Kim, D.R. Williams, S. Emo and M. Acharya, "Modeling pulsed-blowing systems for flow control", *AIAA paper* 02–2728 (submitted to *AIAA J.*).
9. K.B.M.Q. Zaman and J.K. Foss, "The effect of vortex generators on a jet in a cross-flow", *Physics of Fluids*, vol. 9 (1), pp. 106–114, 1997.
10. K.B.M.Q. Zaman, "Reduction of jet penetration in a cross-flow by using tabs", *AIAA Paper* 98–3276, 34th Joint Propulsion Conf., Cleveland, OH, July 13–15, 1998.
11. J.K. Foss and K.B.M.Q. Zaman, "Large- and small-scale vortical motion in a shear layer perturbed by tabs," *J. Fluid Mech.*, Vol. 382, pp. 307–329, 1999.
12. G.N. Abramovich, "The theory of turbulent jets", *The M.I.T. Press*, 1963.